Controller design for a Single-Stage Single-Phase Grid-Connected Solar PV Microgrid

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***Abstract*—The Solar PV based Microgrid is increasing in the small-scale power generation, with the rapid increase in tapping the potential of renewables in power generation. The grid-connected operation of such small-scale grid requires a proper control design operation for effective power injection into the grid line at rated voltage and frequency. This work studies the design of an Integral Terminal Sliding Mode Control (ITSMC) for the controlled switching of the Voltage Source Inverter (VSI), to regulate active power flow into the infinite bus. A 2kW Solar PV system coupled to a 1ϕ 230 V, 50 Hz grid is designed in MATLAB/SIMULINK platform to evaluate the controller performance. The controller response is seen to be robust and also the efficiency of power extraction from the PV source into the grid is achieved around 97% for varying irradiances. For oscillatory response during high temperatures, the controller proves to provide rapid switching signals tracking the deviations appropriately.**

Keywords—Grid-connected, Single-Stage, Integral Terminal Sliding Mode Control, Solar PV Array

I. INTRODUCTION

With the intensified pollution due to fossil fuels and limitations in the availability of conventional resources, the non-conventional sources slowly takes the place of former to provide clean energy. The renewable resources like Solar and Wind are freely available and support clean production of energy as well. However, it is well-known that their presence is seasonal and sporadic. The stable operation of the conventional grids could be more affected with the intervention of microgrids with renewable resources. To integrate these microgrids into the existing grid mandates the support of power electronic switching devices with an effective controller design. The solar PV based microgrid are gaining popularity due to the ease in installation at any area from a roof-top to any wide area coverage. The Solar PV systems could operate in grid connected mode with appropriate operation of a Voltage Source Inverter. The Solar PV array source can be directly plugged to the grid through an inverter in a single stage [1] or it could be connected in two-stage through a DC-DC converter and inverter combination [2]. However, for economy of operation in small scale Solar PV systems, the single stage connection is more appropriate, as it eliminates the need of DC-DC converter.

A Solar PV system requires an MPPT operation for its effective utilization at peak irradiance hours. While interacting with the grid, the voltage source inverter (VSI) acts in a grid following mode with voltage and frequency level of the grid. In this connection, the VSI operates the PV panel at MPP, thereby regulating the maximum power flow to the grid.

The literature predominantly explores the works on two-stage connection decoupling the MPPT control with a DC-DC converter and power flow control for the VSI. The MPPT operation is widely implemented through a separate DC-DC converter as in [3], where exclusive algorithm is studied for MPPT. The VSI plays an inevitable role in the switching of from grid-connected and islanded mode [4] as well. For such operation, linear and non-linear control designs are reported. A VSI can be effectively controlled to address other functionalities relatively like voltage ride through capability and grid synchronization with non-linear controller design [5].

The conventional PI controllers which respond linearly requires more computational efforts for tuning the gain values adaptively to the various modes of operation of grid-tied microgrids. It is effective to select non-linear controllers such as Sliding Mode Controllers [6] to address the multi-functionality requirement of VSI control. When multiple resources come into operation [7], such SMC controllers can provide flexible support with appropriate range tuning. The PR controller could also effectively address the control of VSI [8], while for small scale networks, their computational complexity could provide underdamped response. Also, soft computing techniques like fuzzy logic control [9] providing switching control to VSI, can affect the response under uncertain conditions. The VSI can be controlled in current mode or voltage mode based on the reference for providing switching pulses [10].

In this work, a single-stage grid connected solar PV based microgrid is considered. The VSI interlinking PV source and grid is controlled through an Integral Terminal Sliding Mode Control. The control objective is to regulate the maximum power flow from PV source to the grid irrespective of the intermittencies in PV Irradiance and Temperature profile. This paper presents the Grid-tied microgrid model, the control logic for the VSI and controller response for the variation in PV irradiance and temperature profile.

II. GRID-CONNECTED MICROGRID MODEL

The figure 1 shows the linkage of a Single Stage 1ϕ Grid-Connected Solar PV array. A 2kW solar PV array is connected through a DC-link Capacitor, VSI and an LCL to a 230V rms, 50Hz 1ϕ grid.

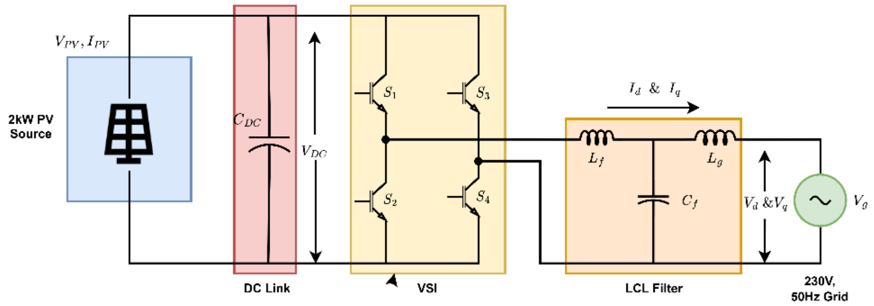

Figure 1: Single Stage 1ϕ Grid Connected 2kW Solar PV Microgrid

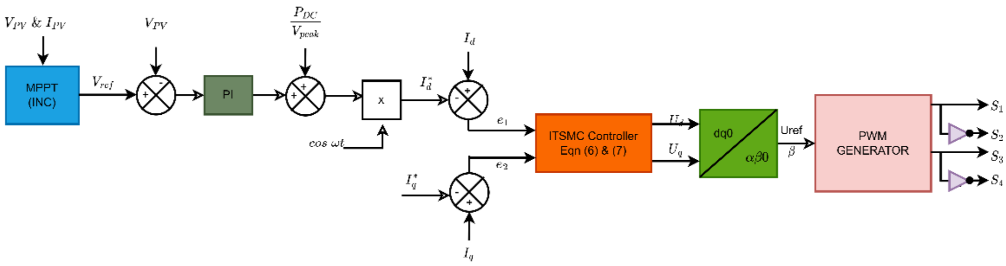

Figure 2: VSI Controller Implementation

III. INVERTER CONTROL

The ITSMC controller is applied to generate the reference signal to provide switching pulses to the VSI. The output voltage and current measured at the output terminals of the LCL filter is resolved into d-q components. The equations are adopted as in [8]. The d-axis current component governs the active power flow whereas the q-axis current component controls the reactive power flow into the grid. The maximum solar power generated is completely injected as active power into the grid. Hence, the d-axis reference current (I_d) is calculated from the maximum power response of PV source tracked using incremental conductance algorithm. The reactive power injected into the grid is set to zero. Hence, the q-axis reference current (I_q) is set to zero.

The error for d-q axis current components is given as,

$$e_1 = I_d - I_d^* \tag{1}$$

$$e_2 = I_q - I_q^* \tag{2}$$

The sliding surfaces (S_1&S_2) are chosen based on error surface of the d-q axis current components. An integral component of the error is added to form the sliding surface, to enhance the controller response to achieve steady state.[8]

$$S_1 = e_1 + K_1 \left(\int_0^t e_1\, dt\right)^{\lambda_1} \tag{3}$$

$$S_2 = e_2 + K_2 \left(\int_0^t e_2\, dt\right)^{\lambda_2} \tag{4}$$

Here $K_i > 0$ and $1 < \lambda_i < 2$ are the controller design parameters

The control law of the sliding surface is given as follows:[8]

$$\dot{S_k} = -\rho_k\, sgn(S_k) \tag{5}$$

Applying the control law and sliding surface chosen, to the VSI state equations for I_d & I_q, the control law to generate switching pulses is obtained as [8]:

$$U_d = \frac{L_f}{V_{DC}}\left(\frac{V_d}{L_f} - \frac{R_f}{L_f} I_d - \omega_0 I_q - \rho_1\, sgn(S_1)\right) + \frac{L_f}{V_{DC}}\left(\dot{I}_d^* - K_1 e_1 \lambda_1 \left(\int_0^t e_1\right)^{\lambda_1 - 1}\right) \tag{6}$$

$$U_q = \frac{L_f}{V_{DC}}\left(\frac{V_q}{L_f} - \frac{R_f}{L_f} I_q + \omega_0 I_d - \rho_2\, sgn(S_2)\right) + \frac{L_f}{V_{DC}}\left(\dot{I}_q^* - K_2 e_2 \lambda_2 \left(\int_0^t e_2\right)^{\lambda_2 - 1}\right) \tag{7}$$

For a 1ϕ grid-connected VSI, the reference signal in dq0 frame is resolved into αβ0 frame, and the β-axis signal is compared with the triangular signal of switching frequency 10kHz. The corresponding pulses is applied for appropriate switching of 1ϕ 2-level VSI.

IV. RESULTS AND DISCUSSION

A 2kW Single Stage 1ϕ Grid Connected PV Source is simulated in MATLAB/SIMULINK R2022a platform, to study the efficacy of the designed Integral Terminal Sliding Mode Controller.

Case 1: Step Change in Irradiance

The power flow from the PV panel to the grid is studied for varying irradiance level as per the pattern shown in Figure 1 (a).

Table 1. PV Panel Efficiency

PV PANEL				GRID	Efficiency
Irradiance (W/m^2)	Voltage (V)	Current (A)	Power (W)	Power (W)	(%)
1000	415.03	5.04	2091.75	2032.76	97.2
800	412.948	4.04	1668.01	1630.63	97.7
700	412.544	3.53	1455.64	1415.83	97.3
600	410.125	3.03	1243.12	1199.28	96.5

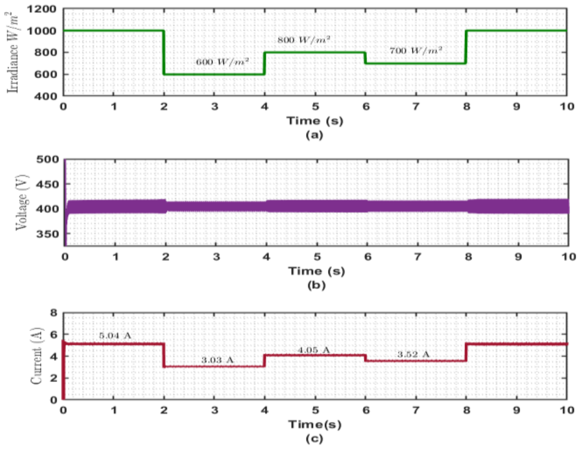

Figure 3 (a) PV Irradiance Pattern (b) PV Output Voltage (c) PV Output Current

The maximum power is extracted from PV array as justified by the change in current level and minor deviations in voltage level at PV panel output (Figure 1(b) & 1(c)). The maximum voltage, current and power at each irradiance level is presented in Table 1, along with the power injected into the grid.

From figure 4(a) & 4(b), for the constant grid voltage, the grid current varies according to the current flow from the microgrid. The PV panel power output and the grid power injected is shown in figure 4(c), which appropriately tracks the change in irradiance level as seen by the variations in

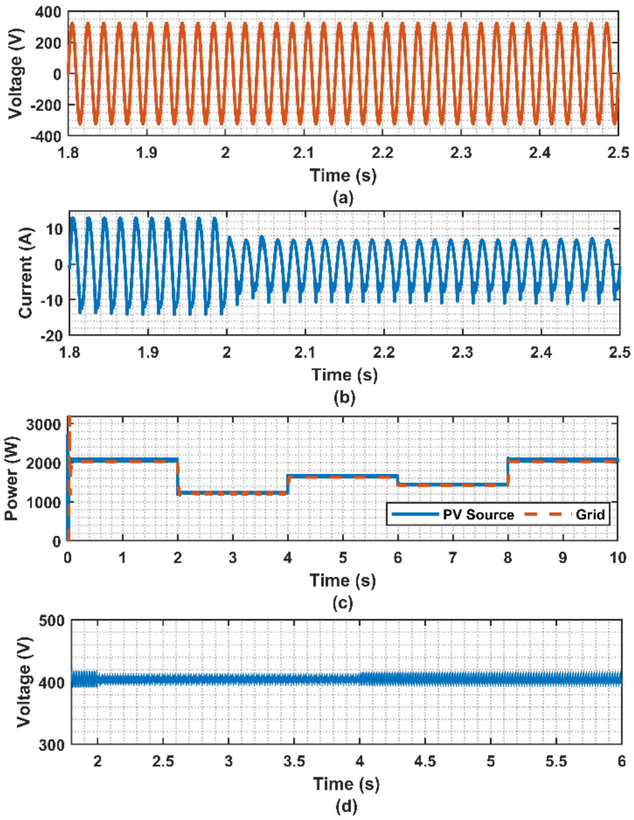

Figure 4 (a) Grid Voltage (b) Grid Current (c) Power (From PV source and to the grid) (d) DC link Voltage

power injected. As a single stage grid connection network is adopted, the PV panel output voltage itself acts as the DC link voltage input for the VSI (fig. 4(d).

The objective of the designed controller is to track the d-q axis current injected into the grid, where the d-axis current (I_d) is regulates the active power flow while the q-axis current (I_q) controls the reactive power injected. The figure 5 (a) & (b) shows the tracking of I_d and I_q, where it could be seen that the actual current value tracks the reference current i.e., the maximum current from PV panel for I_d and zero value for I_q. For instance, at t = 2 s, when the irradiance level steps down from 1000 W/m^2 to 800 W/m^2, it could be seen that appropriately the I_d varies, tracking the reference value. The reactive power fed into the grid from PV panel power is meagre, as the I_q current is tracked near to zero.

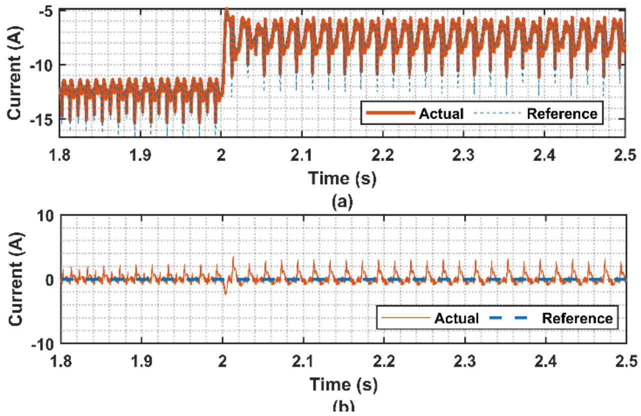

Figure 5 (a) d-axis current (I_d) (b) q-axis current (I_q)

Case 2: Step Change in Temperature

In this case, the irradiance is held constant at 1000W/m^2, while the temperature is varied according to the pattern in fig. 6(a). The PV panel output voltage and current is highly distorted with the change in temperature (Fig 6(b) & (c)). The voltage at the DC link, current injected into the grid and the corresponding power is highly oscillatory due to the impact of temperature changes (Fig 7(a)-(d)).

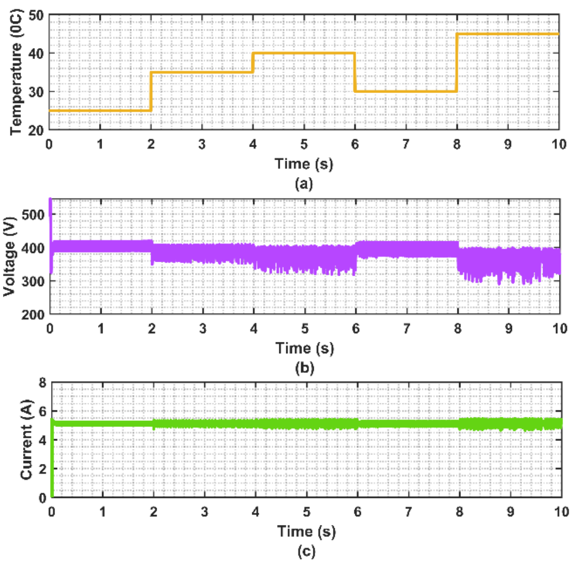

Figure 6 (a) PV Temperature Pattern (b) PV Output Voltage (c) PV Output Current

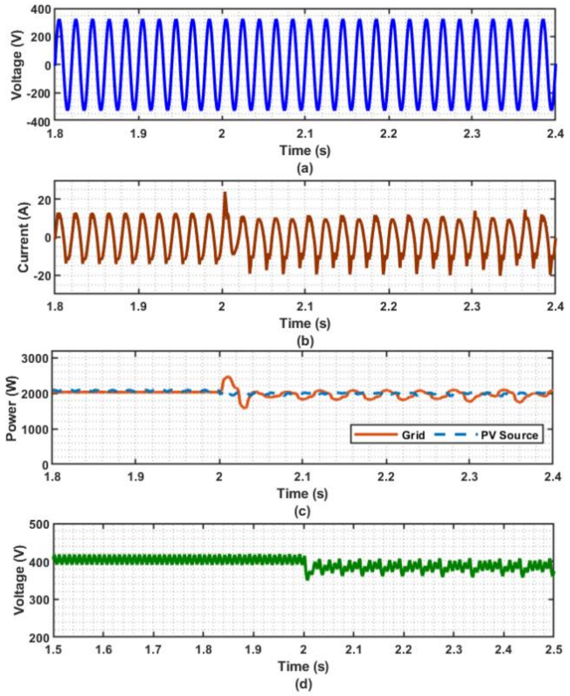

Figure 7 (a) Grid Voltage (b) Grid Current (c) Power (From PV source and to the grid) (d) DC link Voltage

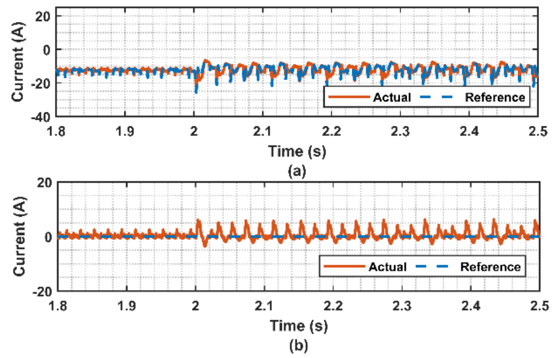

Figure 8 (a) d-axis current (I_d) (b) q-axis current (I_q)

Though the reference current from MPPT algorithm is oscillatory (Fig, 8(a) & (b)), the designed controller accurately tracks the deviations and provides switching signals robustly.

V. CONCLUSION

The design of controller has become a basic element in setup of any microgrid ranging from residential to industrial applications. In view to the injection of power from microgrid into the existing grid, the switching signals to the interlinking VSI is provided from the Integral Terminal Sliding Mode Controller in this work. The single-phase voltage and current at the inverter output is resolved into d-q components to control the active and reactive power correspondingly. With the step changes in irradiance and temperature, it is observed that the d-axis current quickly follows the reference signal obtained from MPPT power achieved. An efficiency of around 97% is achieved for power fed from PV source into the grid. The response of the controller is more stable and robust.

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